

FIELD MONITORING OF SHIP-INDUCED LOADS ON (ALTERNATIVE) BANK PROTECTIONS OF NON-TIDAL WATERWAYS

by

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ABSTRACT

In the seventies, the river Lys was straightened and canalized to allow inland navigation up to CEMT-class IV. Nowadays, on demand of the inland navigation sector, vessels up to CEMT-class Va are allowed as a provisional measure. Due to the intensive navigation the rigid armoured concrete revetment is undermined, which results in progressive bank erosion. To tackle the bank erosion problem, a softer technical-biological revetment type, i.e. off-bank timber piling in combination with (reed)vegetation, is opted for. For a reasonable construction and maintenance cost, environmental benefits are increased and sustainable techniques are attained. But how effective are technical-biological bank protections in operation?

As part of a research project regarding the design of alternative bank protections, we developed a prototype monitoring system along the river Lys at Zulte, Belgium. In 2009, it was initiated and instrumented to acquire field data of the ship wave characteristics, the bank directed slope supply currents and the impact of the ship wave climate on both the conventionally armoured concrete revetment and the technical-biological bank protection. The paper describes the layout of the monitoring system, the applied measurement techniques and the data acquisition process together with the prospects of the ongoing field campaign.

Keywords: ship wave loading, bank protection, working with nature, prototype monitoring

1. INTRODUCTION

Failures of revetments, dikes or other bank protecting structures are mainly the result of tractive forces from currents, water level variations, wind-generated and ship-generated waves. Consequently, a good knowledge of the interactions of these hydraulic stresses with and the geotechnical resistance of the bank protection are relevant for the proper design of embankment structures.

Our case study concerns the (alternative) bank protections along the river Lys in Belgium, which is situated in the north-western part of the Scheldt river catchment. In the seventies, the watercourse was straightened and canalized to allow inland navigation up to CEMT-class IV. Nowadays, the use of larger (and faster) ships prompted the waterway administration to allow vessels up to CEMT-class Va as a provisional measure, in anticipation of a further deepening of the profile in order to gain a narrow (one-way traffic) profile for vessels up to CEMT-class Vb. The river Lys, a non-tidal, confined waterway, has a fixed water level which is maintained in normal weather conditions. Furthermore, high embankments, a small cross sectional width and trees along the crest of the dikes restrict the fetch length for generation of significant wind waves. Consequently, it is believed that ship-generated waves, due to the intensive navigation, contribute the largest amount of erosive energy to the river bank in normal weather conditions, i.e. non-flow dominated situations, causing the undermining of the rigid armoured concrete revetment (Figure 1).

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Figure 1 Undermining of the armoured concrete slabs, resulting in progressive bank erosion.



Figure 2 To tackle the bank erosion problem, a nature friendly bank protection consisting of off-bank timber piling in combination with (reed)vegetation is opted for.

The motivation for the present case study arises from the applied solution method to counteract the progressive failure and erosion mechanism. In an attempt to reconcile both the technical and biological requirements of the revetment, a softer, more nature friendly revetment type, i.e. timber piling in combination with (reed)vegetation, is opted for to tackle the bank erosion problem (Figure 2). For a reasonable construction and maintenance cost, environmental benefits are increased and sustainable techniques are attained. But how effective are technical-biological bank protections in operation?

Navigation generates maximum hydraulic forces on the upper half of the bank protection, around the still water level. Their characteristics, such as propagation directions, wave heights, and wave periods alter with ship design (different types, draught, speed) and navigation orientation and interact with topographic boundaries and local hydraulic conditions. As a result, theoretical calculations of the ship-induced loads on a specific embankment are not straightforward. Accordingly, field measurements provide a welcome alternative for the determination of these forces.

Objective of the present study is to investigate the dynamic interactions between the ship-induced hydraulic stresses on and the geotechnical resistance of the technical-biological bank protection in comparison with the conventional armoured concrete slabs, based on field measurements. The paper will give an overview of the designed prototype monitoring system and applied measurement and data acquisition techniques. First, the field measurement site is shortly introduced. Next, a general description of the ship wave basics is given. Then, the layout of the monitoring system and the applied measurement techniques are discussed in detail and information on the data acquisition is provided. At the end, conclusions are formulated together with the prospects of the ongoing field campaign.

2. STUDY AREA

Site selection was guided by the need to find a location where the river cross section was bounded by both the conventionally armoured concrete revetment and the new technical-biological type of bank protection, each of them installed on one side of the waterway. In this way, both revetment types are subject to similar hydraulic forces and behavioural (dis)similarities related to the incident wave climate can be compared. In addition, it seemed convenient to further select the river cross section in a straight section of the waterway in order to maximize the ship-induced forcing on the revetment. Limit (maximum) speed for displacement ships, and cruising ship speed in case of planing ships, are the best approached in this configuration.

A site in Zulte (Belgium), southwest of the city of Deinze, satisfied all these criteria (Figure 3). It is located in the most downstream part of the canalized river Lys, 1.5 km before the river's splitting into the Schipdonk canal and the Tourist Lys (meandering part of the river Lys between the cities of Deinze and Ghent). Peak discharges of 200 m³/s might occur occasionally, however, the regulated water level of 5.61 m TAW corresponds to an average discharge of 30 m³/s (HIC, 1983-2009).

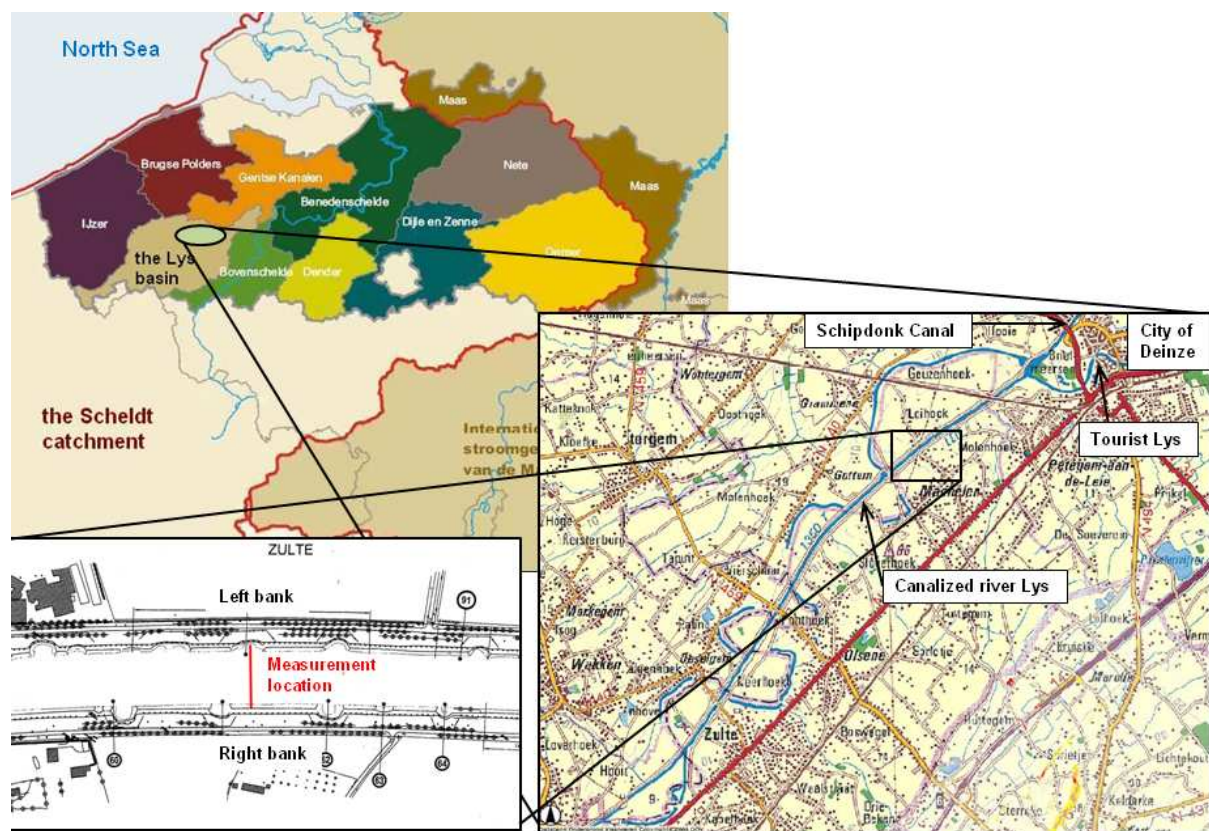


Figure 3 Location of the prototype monitoring system on a river cross section of the canalized river Lys at Zulte (Belgium).

At the measurement location, the river Lys is approximately 50 m wide (width on free water surface) and 3.5 m deep, and has a broken trapezoidal cross section. Locally however, heavy shipping traffic caused scour of the subaqueous slope which resulted in the disappearance of the underwater berm. The right bank of the cross section is protected against wave attack by armoured concrete slabs, resting on a grider toe protection (Figure 4). The left bank of the river is defended by a more nature friendly bank protection consisting of off-bank timber piling in combination with (reed)vegetation (Figure 5). Originally, armoured concrete revetment protected this embankment as well, but undermining of this rigid structure led to progressive bank erosion and the presence of a vertical cut-bank. At its base a very gentle sloping beach of eroded sediment is found, partly colonized by (reed)vegetation. The working principle of the applied technical-biological method relies on the reduction of the excessive kinetic wave energy by a single row of timber piles in front of the bank down to a manageable level in the water strip behind, where wave energy is further dissipated by (reed)vegetation before reaching the river bank.

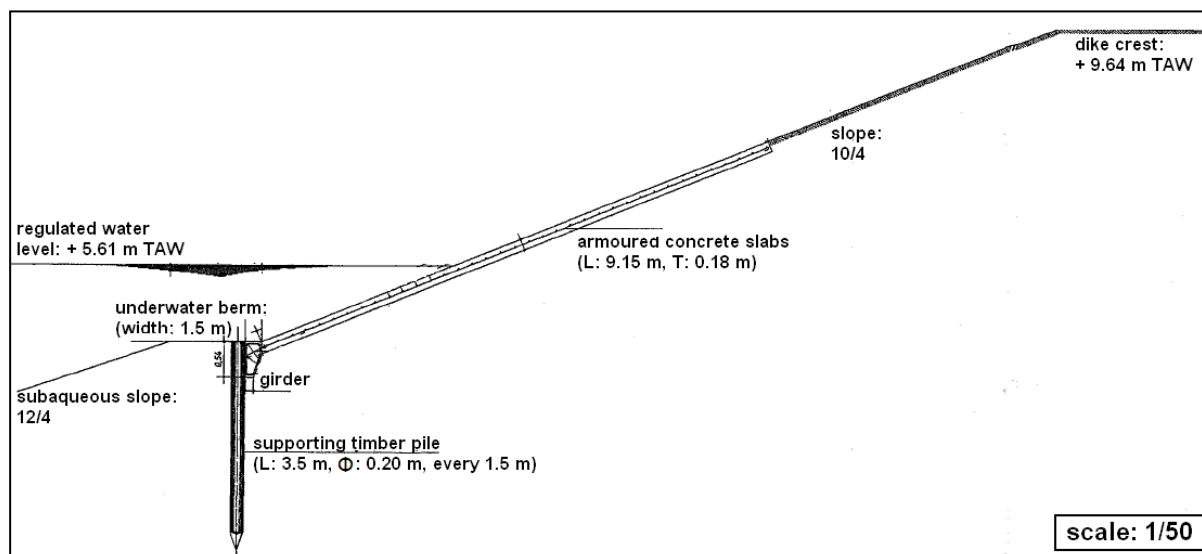


Figure 4 Cross section of the right bank at the measurement location: bank protection by means of armoured concrete slabs (adapted from drafts of W&Z)

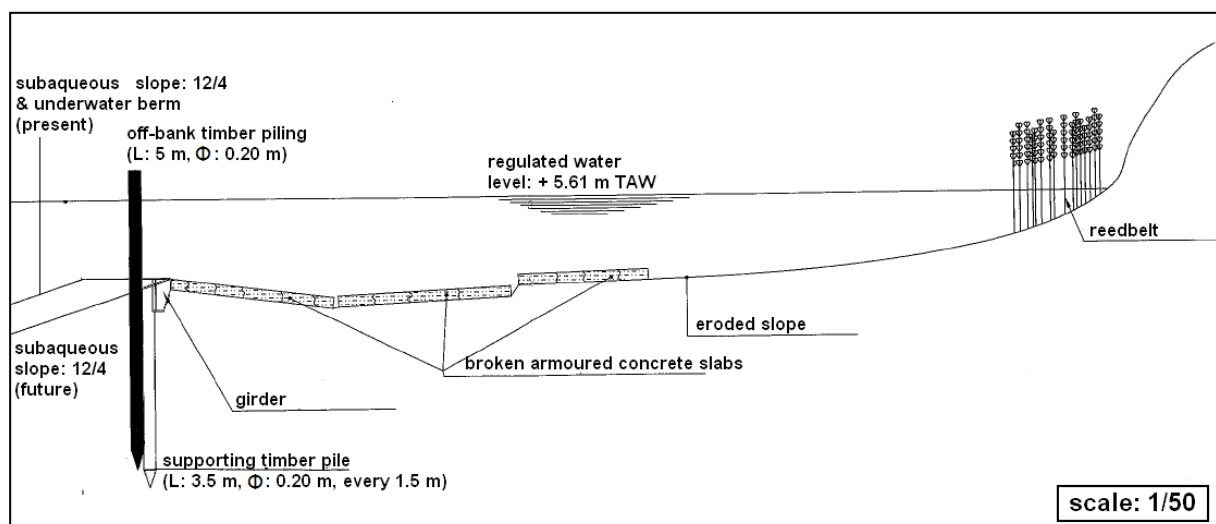


Figure 5 Cross section of the left bank at the measurement location: bank protection by means of off-bank timber piling in combination with (reed)vegetation (adapted from drafts of W&Z)

3. BASICS

Ship-generated waves have their distinct characteristics in comparison with wind-generated waves. Navigating ships generate a specific pattern of surface waves, which can be separated into the primary and secondary wave system of a ship. Although the duration of the wave train of a ship is very limited at a given location, it is a complex wave pattern, consisting of different components which are frequently superimposed.

The primary wave system, propagating in the navigation direction, is characterized by a significant water level depression along the hull of the ship. It is initiated with a front wave at the bow of the ship, travels as a drawdown wave along the ship and ends with the stern wave. Associated with these characteristics is the return current. In order to overcome its resistance, the navigating ship transfers energy to the water body in the form of a water displacement from the front to the back of the ship, inducing a return current.

Transverse and diverging secondary waves, propagating under an oblique angle to the sailing line of the ship, are caused by the pressure pattern due to discontinuities in the hull profile (Schiereck, 2001).

The secondary wave train usually consists of two higher waves followed by 10 to 15 smaller waves. It typically has a shorter wave period compared to the primary wave period.

The primary wave and secondary waves generate a constant wave pattern with interference cusps formed on a line with an angle of $19^{\circ}28'$ to the sailing line of the ship in deep water (Figure 6). These wave patterns were first investigated by Lord Kelvin in 1887. The direction of propagation of the interference cusps is then at an angle of about 35° with the sailing line, hence the angle of approach for a bank parallel to the sailing line is 55° .

Figure 6 depicts both the primary and the secondary wave system. All observable parameters of the ship wave pattern for a ship navigating at subcritical speed are illustrated in Figure 7. The magnitude and thus, relevance of these parameters varies with the characteristics of the navigating ship and the local geometry of the waterway.

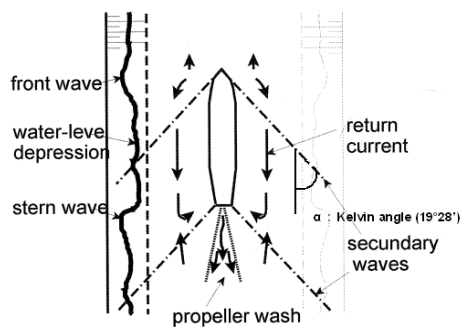


Figure 6 Primary and secondary wave system around a navigating ship (adapted from Schiereck, 2001)

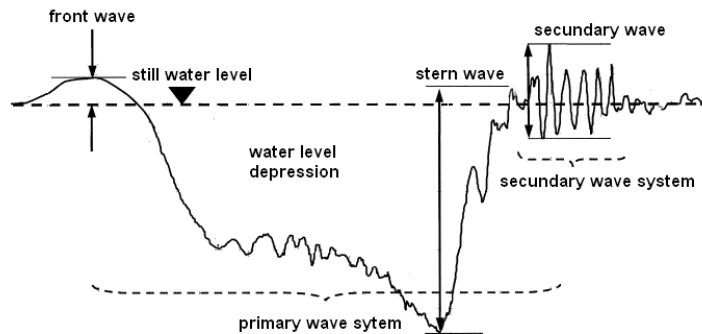


Figure 7 Parameters of the ship wave pattern for a ship navigating at subcritical speed.

4. MONITORING SYSTEM

4.1 Layout

The different physical processes that are measured on and near the two bank protection types are listed in Table 1. Figure 8 and Figure 9 present the position of the measurement devices on the armoured concrete slabs (site A) and on the technical-biological bank protection (site B) respectively.

At site A, one pressure sensor is mounted on the bottom end of the step gauge. At site B, pressure sensors are deployed in a cross-shore array. Pressure sensor C (on Figure 9) is located very close to the bank, inside a reed patch, with the other gauges located sequentially further into the waterway, up to a distal point of 15 m from the bank and 1.5 m before the off-bank timber piling (A on Figure 9). Pressure sensor B (on Figure 9) is fixed onto a moveable lateral arm in order to have the possibility of measuring the transmitted wave pattern on variable distances of the off-bank timber piling. The wave run-up and run-down profile on the conventional revetment is detected by means of a step gauge, installed on the slope of the armoured concrete slab.

Two suspended solids concentration profilers are deployed in the water strip behind the off-bank timber piling (D on Figure 9). Both instruments are fixed onto a moveable lateral arm in order to have the possibility of measuring the suspended solids concentration profile of the water column on variable distances of the off-bank timber piling. The measurement device detects suspended solids in the water column and records their reflections and the dynamic parameters. By analysing additional water samples, the suspended sediment content of the suspended solids volume is determined and hence, the suspended sediment transport due to shipping traffic can be quantified. The distance between the sailing line and the river banks is determined using a laser distance meter (E on Figure 9). The laser beam continuously measures the width of a fixed river cross section. When a ship passes this cross

section, the measured distance is reduced to the spacing between the hull of the ship and the position of the laser distance meter.

The actual number of ship passages at the measurement site can be checked by the ship data of the sluice at Sint-Baafs-Vijve, located 8 km upstream of the measurement site and operated by the Flemish Administration of waterways and the sea canal. This holds just a rough evaluation of the detected ship passages because recreational boat traffic can bypass the sluice. Ship information of the sluice is further used for the calculation of the ship speed. Combining the length of the hull with the duration of a ship passage gives the ship's speed. To facilitate the identification of a ship, a camera, triggered by the reduction in measured distance of the laser distance meter, takes a picture of the passing ship (F on Figure 9).

Additionally, water level data are available from the gauging stations of Deinze and Sint-Baafs-Vijve, operated by the Hydrologic Information Centre (HIC) of the Flemish Government, in order to detrend the pressure time series, i.e. remove the mean water level of the water elevation time series, such that the characteristic water level fluctuations occasioned by a ship passage can be identified.

Physical process	Instrument	Methodology
Wave run-up on the slope of the armoured concrete revetment	1 step gauge	Step gauge on the armoured concrete slab: continuous measurement of water elevation time series
Incident waves in front of the armoured concrete revetment	1 pressure sensor	Pressure sensor under step gauge: continuous measurement of pressure time series, conversion of water pressure to water elevation
Incident waves in front of the off-bank timber piling	1 pressure sensor	Continuous measurement of pressure time series
Transmitted waves behind the off-bank timber piling	1 pressure sensor	Continuous measurement of pressure time series
Attenuated waves in the (reed)vegetation belt	1 pressure sensor	Continuous measurement of pressure time series
Suspended sediment transport	2 suspended solids concentration profilers	Continuous measurement of the optical backscatter response of suspended solids
Ship speed	1 laser distance meter	Indirect calculation of local ship speed based on duration of ship passage at the measurement site and length of the hull
Data acquisition	1 data logger at each river bank	Signal conditioning electronics, data acquisition hardware, data storage and data back-up

Table 1 Equipment of the prototype measurements on the armoured concrete revetment and the technical-biological bank protection.

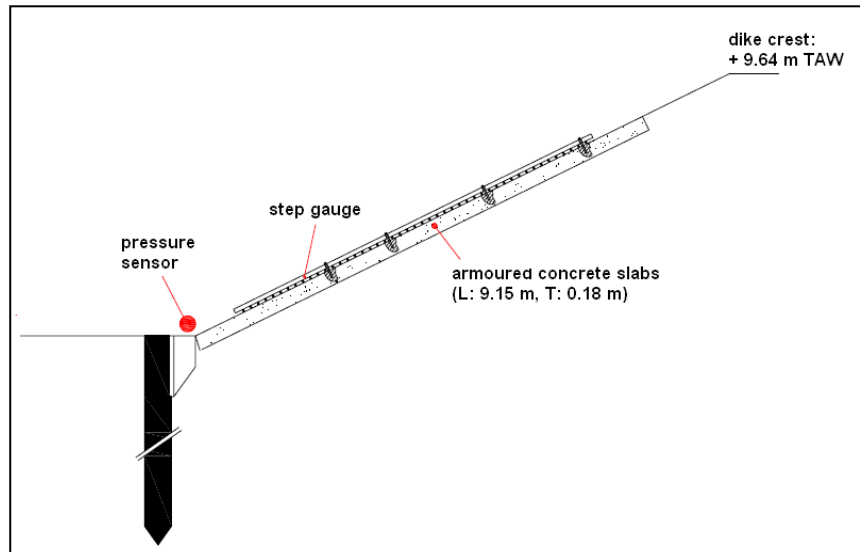


Figure 8 Prototype monitoring sytem on the armoured concrete revetment (site A).
Location of the measurement devices.

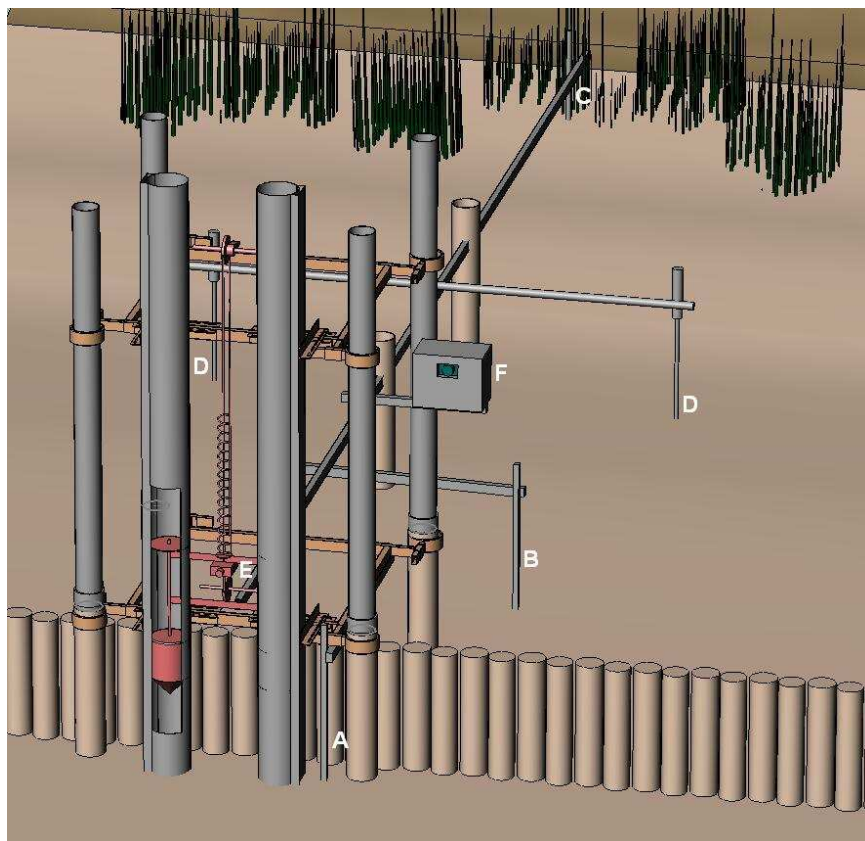


Figure 9 Prototype monitoring sytem on the technical-biological bank protection (site B).
Location of the measurement devices.

4.2 Technical description of the instrumentation

Pressure sensor

Four Druck PTX 1830 pressure sensors (GE Sensing & Inspection Technologies, Leicester, UK) have been installed. The pressure gauges were laboratory calibrated via a progressive stepwise hydraulic pressure generation with a pressure calibrator, determining the scaling and offset parameters of each sensor. Output voltages at fixed pressures were recorded for 100 bursts and averaged.

The sensors are completely submersible and are protected against corrosive environments by a welded titanium body. Venting tubes connect the rear side of the membrane of the sensors with the atmospheric air pressure implying that relative pressure is measured. The output signal of the sensors is current modulated: the pressure is converted to a current in the range of 4 to 20 mA. In this way, the output signal is on the same wire as the power supply. All pressure sensors operate a factory set measurement range from 0 to 1 bar. They have a six times permissible overpressure and the signal precision to linearity is specified to be $\pm 0.06\%$ of full-scale of the best straight line.

Step gauge

The step gauge was designed and assembled at the Coastal Engineering Department of Ghent University. The step gauge consists of an 4.80 m long glass fibre reinforced polyethylene tube with 48 embedded electrodes, placed at equidistant intervals of 100 mm. The electrodes only detect water when in full contact with the water mass (to avoid that drops give an erroneous signal). In this way, the step gauge is able to register the water elevation, and thus the wave run-up and run-down profile, in steps of 100 mm.

A detailed description of the measurement device can be found in Van de Walle et al. (2006).

Laser distance meter

The laser distance meter DLS-B 15 (Dimetix, Herisau, Switzerland) consists of an IP65 body in which the light source and receiver optics are put, together with a screw terminal containing the analogue and digital output. The device allows contactless distance measurements of natural surfaces in the range of 0.05 to approximately 65 m, using the reflection of a laser beam (laser class II, < 0.95 mW). The typical measurement accuracy is indicated to be 1.5 mm. A time of 0.15 to 4 s is needed to measure a single as well as a tracking distance.

The instrument also includes the option of triggering other measurement devices by means of configuring one digital output as a digital input. Making use of this utility, the push button of the photo camera is triggered by the distance meter when a reduction in the measuring distance occurs, owing to (most of the time) a ship passage.

Suspended solids concentration profiler

The suspended solids concentration profiler ASM-IV (Argus, Ritterhude, Germany) is 2.4 m long and consists of a battery powered central unit in the head of the instrument and a 1.44 m long stainless steel rod with an active board of backscatter infrared laser sensors (850 nm), embedded in a special polyurethane casting resin which must prevent the board from breaking.

The optical sensors are placed at a distance of 10 mm, which means that 144 sensors are mounted. The maximal sampling volume is 10 cm³; the actual sample however depends on the density of the solids suspension in a distance range of 0 up to 100 mm in front of every individual sensor. The accuracy of the optical backscatter sensors is specified to be 10%, with an operating resolution of 5%. The sealed in central unit consists of a microprocessor, a data memory, additional pressure, tilt and temperature sensors and the energy supply.

5. DATA ACQUISITION

All measurement devices, except the stand alone suspended solids concentration profilers, deliver an output signal that is transmitted through cables to locked storage boxes, located on each river side.

The current modulated signal of the pressure sensors is there converted to a voltage modulated signal, varying between 0.48 and 2.42V. The voltage outputs from the pressure sensors are then separately connected to an analogue low-pass filter to eliminate high-frequent noise. Subsequently, the data acquisition hardware converts the voltage signals of all 4 channels on line into digital data, using a sampling frequency set to 10 Hz. After Analogue-to-Digital conversion, the raw data is stored in a binary file on a memory card located in the data logger.

The step gauge and the laser distance meter are connected to the same data logger by means of a digital serial output. The raw data of these devices is appended to the binary file containing the pressure time series.

Off line, the raw data is prepared for processing by reorganising from a per time in a per channel structure. Therefore, a software package including several signal processing tools for application on the time series of the pre-processed data is established. Software tools are available to read data from file, display data on screen, select pieces of data and analyse the selected data.

Data acquisition of the suspended solids concentration profilers can easily be done by placing an optical communication unit on the head of the instrument. An optical IRDA- serial port is integrated in the head housing, making communication feasible without opening the instrument. In this way, data can be directly read out on a laptop using the ASMA software and further processed.

6. CONCLUSIONS AND OUTLOOK

The ship wave climate depends not only on the characteristics of a navigating ship, but also on the hydraulic and geometrical boundary conditions. On-site prototype research into the dynamic interactions between the ship-induced hydraulic stresses on and the geotechnical resistance of the technical-biological bank is thus very relevant in order to determine how effective more nature friendly bank protections are on confined, non-tidal waterways subject to heavy shipping traffic. In addition, the field measurements will point out the (proper?) functioning of the presented technical-biological bank protection under given conditions and hence, extended and refined design rules can be developed in a further research stage.

In this paper, the prototype monitoring system, deployed along the river Lys at Zulte, Belgium, is described. The system is equipped to acquire data of the ship wave characteristics (incident, transmitted and attenuated waves), the bank directed slope supply currents (wave run-up and run-down) and the impact of the ship wave climate (suspended sediment transport) on both the conventionally armoured concrete revetment and the technical-biological bank protection.

Use is made of 4 pressure sensors, a step gauge, 2 suspended solids concentration profilers, a camera and a laser distance meter. These measurement techniques also give the possibility to roughly identify the threshold at which the energy of ship-generated waves is able to overcome the bank protection's resistance and cause pronounced erosion.

On-site data acquisition is centralised in two data loggers, except for the stand alone suspended solids concentration profilers. On line Analogue-to-Digital conversion takes place when necessary, after which the raw binary data is stored on a memory card.

7. ACKNOWLEDGEMENTS

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